Modelling of Wind Direction Signals in Polarimetric Sea Surface Brightness Temperatures

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Abstract A preliminary geophysical model function, relating the sea surface brightness temperatures to ocean surface wind speed and direction, was developed using the data acquired at 45°, 55°, and 65° incidence angles by Jet Propulsion Laboratory's (JPL) aircraft 19 and 37-GHz polarimetric radiometers in 1994 and 1995. Radiometric temperatures from all polarization channels under cloud- free conditions showed clear dependence on surface wind direction. When there were stratus or scattered clouds, T_v and T_h were significantly influenced by the radiation from cloud water, but the polarimetric channel U was found to be insensitive to clouds. The Fourier harmonic coefficients of the wind direction signals were derived from experimental data and related to the wind speed and direction, incidence angle and frequency. In general, all harmonic coefficients increase from low to moderate wind speeds, except the sin 2ϕ component of U at 65° incidence, which peaked at low winds with a peak-to-peak amplitude of 0.6 to 1 Kelvin at about 3 m/s winds. At moderate wind speeds, 45° incidence angle exhibits larger second harmonic signals, but smaller first harmonic signals, than higher incidence angles. Wind direction signals were similar in 19 and 37 GHz channels, but the 37 GHz channel showed a slightly stronger wind direction sensitivity than the 19 GHz channel. The results suggest promising applications of passive microwave radiometers to ocean wind vector measurements.

INTRODUCTION

There has been an increasing interest in the application of passive microwave radiometers for ocean wind vector measurements [1]- [9]. Aircraft, radiometer measurements performed at near normal incidence angles [1, 7], the SSM/I data at 53° incidence angle [2], and the aircraft polarimetric radiometer measurements acquired at 30° to 50° [8] have found the dependence of sea surface brightness temperature on wind direction over a large range of incidence angles. However, these experimental data are insufficient for designing a spaceborne sensor for ocean wind sensing. To obtain a better understanding of the frequency dependence, a Ka-band (37 GHz) polarimetric radiometer was built and integrated with the K-band (19 GHz) radiometer used in the 1993 WINDRAD experiments [8]. The dual-frequency system was integrated with the NASA DC-8 and flown in July-August 1994 and March-May and September 1995 over ocean buoys to obtain more extensive measurements from 45° to 65° incidence angles.

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MICROWAVE POLARIMETRIC RADIOMETRY

Electromagnetic waves emitted from natural media due to random thermal motion of electric charges are in general partially polarized. To fully characterize the polarization state of a partially polarized thermal radiation requires four Stokes parameters I, Q, U, and V. $I = T_v + T_h$ represents the total radiated energy and $Q = T_v - T_h$ the polarization balance. T_v and T_h are the brightness temperatures of vertical and horizontal polarizations, while U and V characterize the correlation between these two orthogonal polarizations. A typical approach for U and V measurements is to carry out the power measurements at 45°-linear, - 45°-linear, left-hand-circular, and right-hand circular polarizations. By denoting the brightness temperature measurements at these four polarizations as T_{45}, T_{-45}, T_L, and T_R, U and V can be derived from these four brightness measurements as $U = T_{45} - T_{-45}$ and $V = T_L - T_R$.

For wind-generated sea surfaces, the surface spectrum is expected to be symmetric with respect to the wind direction (ϕ_w). Denote the azimuthal observation angle of radiometer look direction with ϕ_r and the relative azimuth angle with $\phi = \phi_w - \phi_r$. Yueh et al. [10] derived from Maxwell's equations using reflection symmetry that T_v and T_h are even functions of ϕ and U and V are odd functions of ϕ. Hence, expanded to the second harmonic of ϕ,

$$T_v \simeq T_{v0} + T_{v1} \cos\phi + T_{v2} \cos 2\phi \qquad (1)$$

$$T_h \simeq T_{h0} + T_{h1} \cos\phi + T_{h2} \cos 2\phi \qquad (2)$$

$$U \simeq U_1 \sin\phi + U_2 \sin 2\phi \qquad (3)$$

$$V \simeq V_1 \sin\phi + V_2 \sin 2\phi \qquad (4)$$

All coefficients are functions of surface wind speed, incidence angle, and frequency. There are also indications that the sea surface spectrum is influenced by the presence of large waves and the atmospheric boundary layer stability. Since sea surface brightness temperatures are influenced by the surface scattering, it is therefore possible that the harmonic coefficients are also functions of surface temperatures and significant wave height.

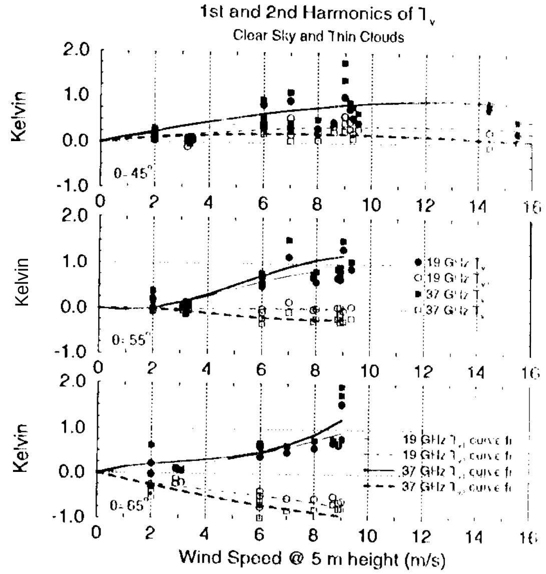

Figure 1. T_{v1} and T_{v2} from 19.35 and 37 GHz JPL wind radiometer channels versus wind speed at 5 m elevation (a) $\theta = 45°$, (b) $\theta = 55°$, and (c) $\theta = 65°$.

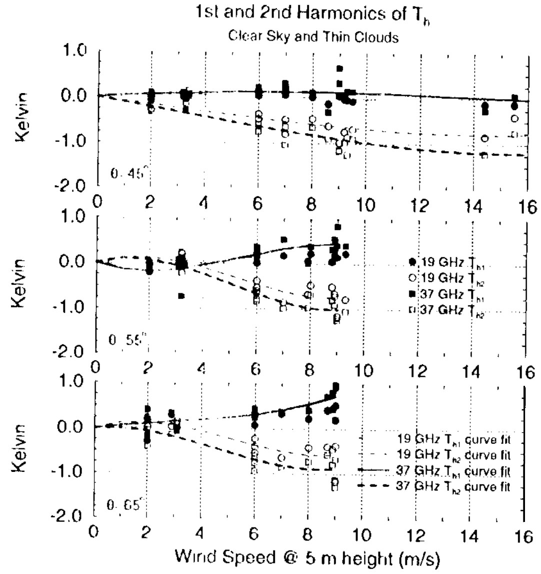

Figure 2. T_{h1} and T_{h2} from 19.35 and 37 GHz JPL wind radiometer channels versus wind speed at 5 m elevation. (a) $\theta = 45°$, (b) $\theta = 55°$, and (c) $\theta = 65°$.

PRELIMINARY GEOPHYSICAL MODEL

A dual-frequency polarimetric radiometer system operating at 19 GHz (K band) and 37 GHz (Ka band) has been built and installed on the NASA DC-8 aircraft for ocean wind measurements. This dual-frequency system was an upgrade of the 19 GHz polarimetric radiometer used in the first WINDRAD experiment in November 1993 [8]. A series of aircraft flights were carried out in 1994 and 1995 to acquire polarimetric sea surface brightness temperatures with the dual-frequency polarimetric radiometer system. Circle flights were performed over the National Data Buoy Center (NDBC) moored buoys deployed off the US west coast, which provided ocean wind speed and direction measurements. A set of flights were performed near the Hurricane Juliette in September 1995, and the ground truth was obtained by the dropsonde launched from the DC-8. The K- and Ka-band antenna horns were mounted on the DC-8 windows at a fixed angle. The DC-8 was banked at three different angles to measure the data at the nominal incidence angles of 45°, 55°, and 65°, and performed circle flights to acquire data from all azimuth angles with respect to the surface wind direction. There were clear wind direction signals in all polarization channels under clear sky conditions. When there were stratus or scattered clouds, the radiation from clouds would obscure the wind direction signals in T_v and T_h, but had no significant influence on the azimuthal modulations in U.

The Fourier coefficients shown in Eqs. (1) to (3) were calculated with a minimum mean square error fit to the data. Figures 1 to 4 illustrate the harmonic coefficients for the data acquired for clear skies and thin clouds. In general, all harmonic coefficients had an increasing trend from low to moderate wind speeds, except U_2 at 65° incidence, which peaked at about 3 m/s winds. These figures show a few Kelvin peak-to-peak signals in $Q = T_v - T_h$ and U channels at moderate wind speeds, but only a few tenths of one Kelvin at 2 to 3 m/s winds. The harmonic coefficient, which is most sensitive to the wind direction at low winds, is U_2 at 65° incidence. It is unclear why U_2 at 65° peaked at about 3 m/s wind speed, but low wind measurements from 1994 and 1995 confirmed the repeatability of this signal.

The signatures of 19 and 37 GHz data are very similar for all incidence angles. This was observed in all data collected throughout the flight experiments. This could be due to the nature of sea surfaces, which are known to have a wavenumber spectrum closely following a power law, and are thus nearly self-similar at various scales like a fractal surface. Hence, although 19 and 37 GHz thermal emissions interact with different parts of the spectrum, the length scales of surface dominating the scattering would appear similar at these two frequencies, if normalized by the electromagnetic wavelength. However, the 37 GHz channel was shown to be more sensitive to the wind direction than the 19 GHz channel. We do, however, expect that the 19 GHz channel to be less sensitive to atmospheric effects than the 37 GHz channel.

SUMMARY

A preliminary geophysical model function for the sea surface brightness temperatures in incidence angle range of 45° to 65° was developed using the data from a series of dual-frequency airborne radiometer flights in 1994 and 1995. Dependence of the wind direction signals in polarimetric brightness temperatures on frequency, incidence angle, and wind speed were discussed. Further flight experiments to acquire data at high wind (above 15 m/s) are necessary for a more complete evaluation of the wind speed dependence of wind direction signals. The effects of other atmospheric and oceanic variables, such as air and sea surface temperatures (SST) and significant wave height also need to be quantified to understand the lim-

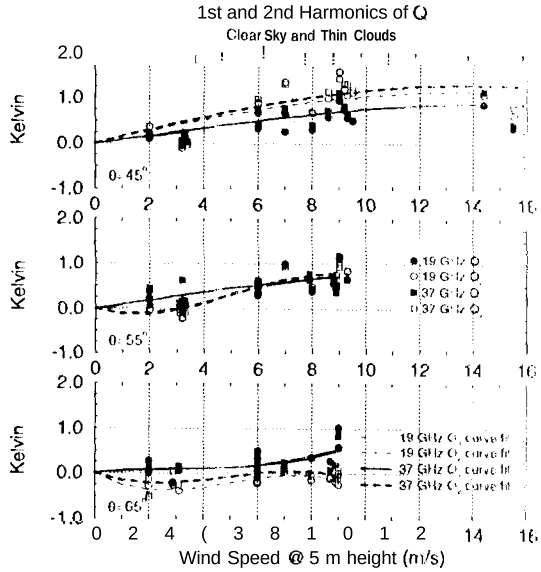

Figure 3. Q_1 and Q_2 from 19.35 and 37 GHz JPL wind radiometer channels versus wind speed at 5 m elevation. $Q = T_v - T_h$. (a) $\theta = 45°$, (b) $\theta = 55°$, and (c) $\theta = 65°$.

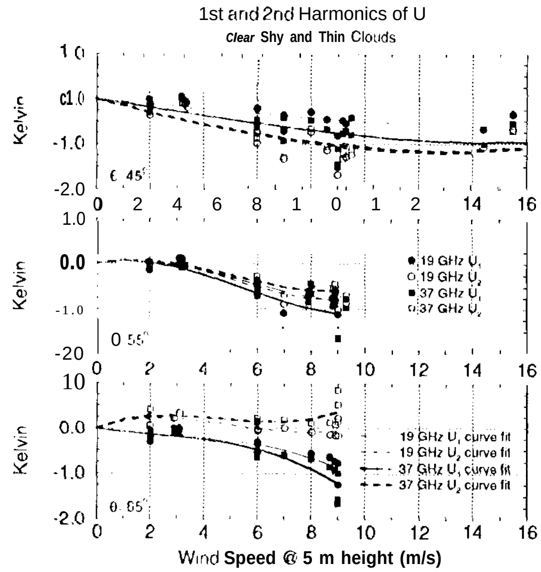

Figure 4. U_1 and U_2 from 19.35 and 37 GHz JPL wind radiometer channels versus wind speed at 5 m elevation. $U = T_{45} - T_{-45}$. (a) $\theta = 45°$, (b) $\theta = 55°$, and (c) $\theta = 65°$.

itation of passive microwave radiometry and to develop techniques to reduce these effects.

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